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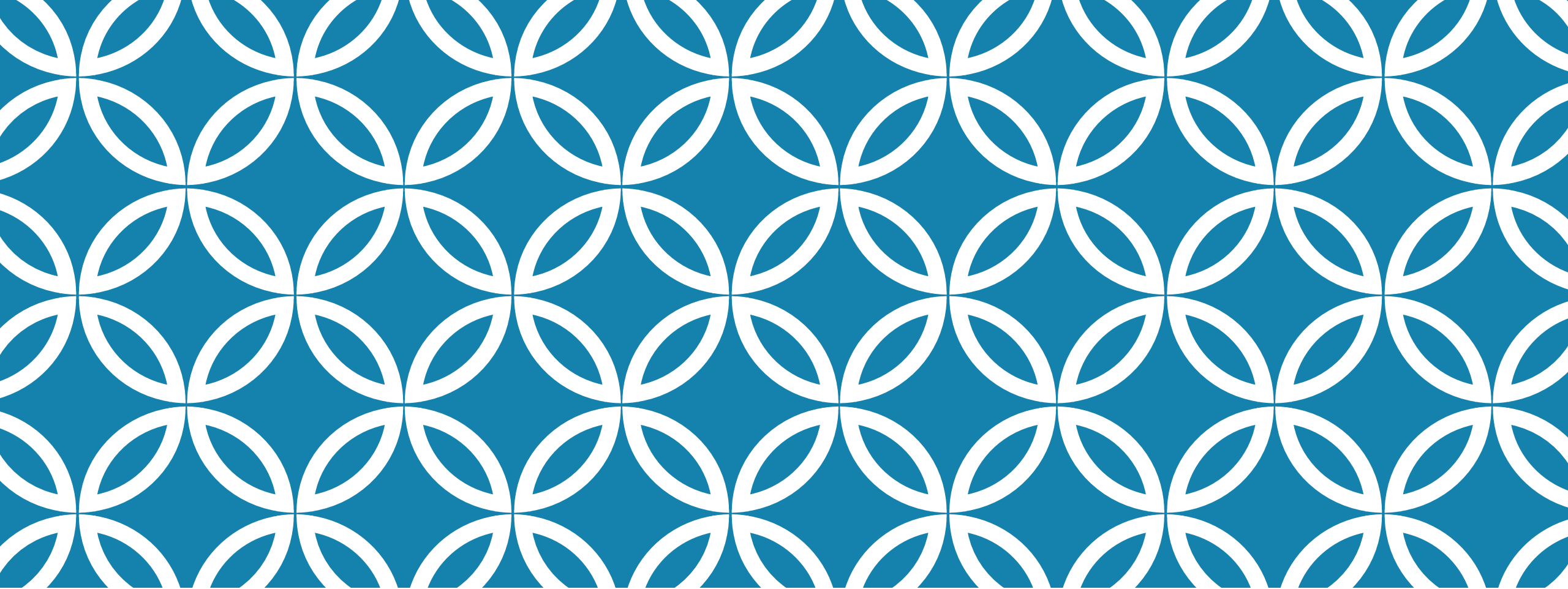
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THE TERRESTRIAL ENVIRONMENT AND THE MANY OPEN QUESTIONS WE HAVE ON NEUTRON RADIATION EFFECTS

Heather Quinn

SOURCES

JESD89 (will talk more about this next week)

Eugene Normand's work from the 1990s.

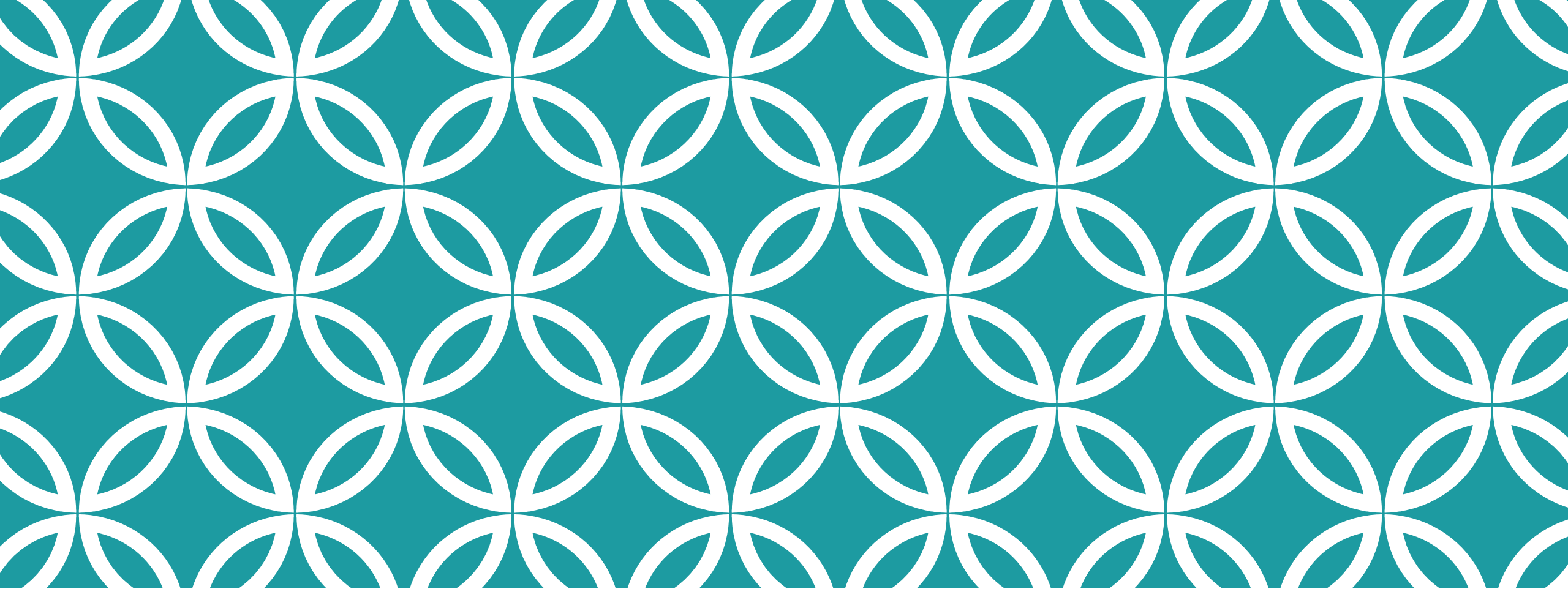
THE TERRESTRIAL ENVIRONMENT

It is a bit more complex than the space environment, due to the interaction with the atmosphere:

- Primary cosmic rays scatter on nitrogen and oxygen in the atmosphere
- Starts a cascade of pions, muons, protons and neutrons through the atmosphere
- The protons and neutrons at the top of the atmosphere are higher energy than at the bottom
- Pions do not make it past the “hadron cutoff” at 40K’

Besides that, it is greatly affected by surroundings:

- Anything with hydrogen can moderate it: jet fuel, concrete in building materials
- Some materials make it worse: granite in buildings on the east coast
- Arguments amongst physicist: does the temperature of the room affect the energy of the neutrons?
Maybe Jeff can explain that one to us, because I surely do not get it



THE QUIRKINESS OF NEUTRONS



NEUTRON ENERGIES

There are four basic energy ranges that we use:

- Fast neutrons
- Epithermal neutrons
- Thermal neutrons
- Cold neutrons

I think there is only agreement on the thermal neutron energy ranges. This is what we will use:

- Fast: 0.1 MeV and up, because these energies all cause the (n, Si) reaction
- Thermal: 0.025 eV (notice the change in units), and it dominates the (n, B10) reactions
- Epithermal: everything in the energy range between fast and thermal
- Cold: everything lower in energy than thermal, which has even worse (n, B10) reactions than thermal neutrons, but they don't exist in great quantities in the environment

THE THING ABOUT NEUTRONS

Neutrons are not like protons

Protons are incredibly stable

- Proton decay is only a theory that has never been measured
- It is why LEO is such a PITA, because those protons are never going away

Free neutrons (unbound from an atom) are really unstable. A free neutron can only exist 10-11 minutes approximately. In 10-11 minutes it needs to:

- Absorb into an atom
- Beta decay into a proton

That generally means that the lower energy neutrons are about done

THE OTHER THING ABOUT NEUTRONS

The lack of charge makes them move more classically:

- Neutrons only change directions by scattering. You cannot steer neutrons with magnets, like protons and heavy ions.
- The neutron mean free path is massive – a 3 MeV neutron can go km in air without scattering
- Each time a neutron scatters, it can retain up to $\frac{1}{2}$ of its energy, so it takes 20-30 scatters to get a neutron from 800 MeV \rightarrow 0 MeV. Most of those scatters are below 10 MeV. The first few scatters knock off a lot of the energy

All of this means:

- Neutrons are hard to shield
- Neutrons make it from the top of the atmosphere to the bottom, although less at the bottom than the top

There is a good resource here:

http://www.radioactivity.eu.com/site/pages/Neutrons_Effects.htm

THE EFFECT OF SCATTERING ON DIRECTIONALITY ON FLUX

Unlike space, fast neutrons are directional

- Primary cosmic rays are roughly perpendicular to the ground on entry
- Resulting flux only changes direction by scattering

Scattering causes neutrons to change directions, but only by small angles

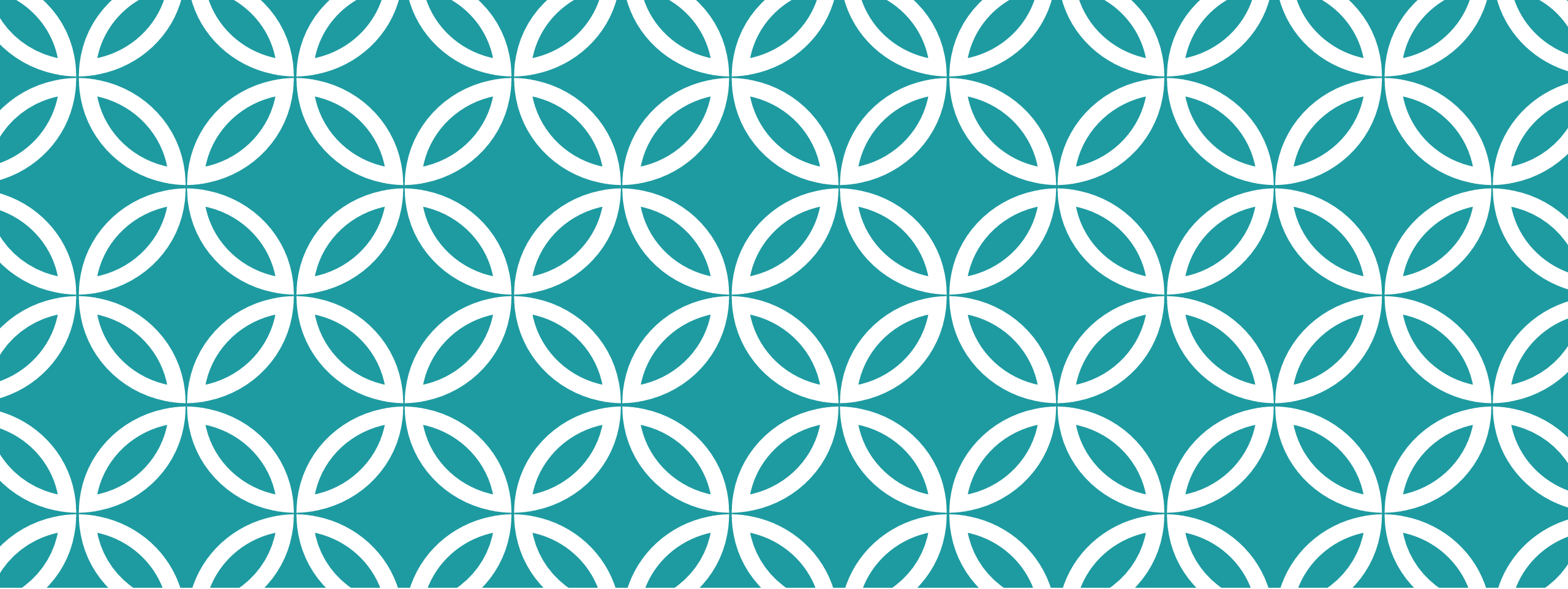
- Fast neutron flux might only scatter a few times, so still mostly perpendicular
- Thermal flux has scattered 20-30 times and is considered omnidirectional

What does this mean?

It is actually confusing for testing: we need to align the systems in the beam as it is in the deployed system

- Do we even know that?
- If you do, test accordingly
- If you don't, test at a normal incidence

Does angle of neutron testing matter? Likely yes, but there is so little data that it remains an open question



NEUTRON FLUX AND SPECTRA



THE DETAILS ON THE NEUTRON ENVIRONMENT

Most up to date information is in the JESD89A. JESD89B is coming out eventually, but not yet.

- They maintain a reference flux for determining SER or FIT rates in NYC (actually East Fishkill)
- Mike Gordon from IBM did this work for JESD89A
- Paul Goldenhagen from DHS did this work for JESD89B
- These numbers are actually changing from A to B

The JEDEC community maintains seutest.com, which provides information about the neutron flux in all ground locations. This will be updated with the JESD89B.

QARM can also help you determine neutron fluxes and error rates for airplanes

THE EFFECT OF ALTITUDE ON NEUTRON FLUX

This is an exponential relationship, and airplanes work in a much harsher radiation environment than ground-level electronics.

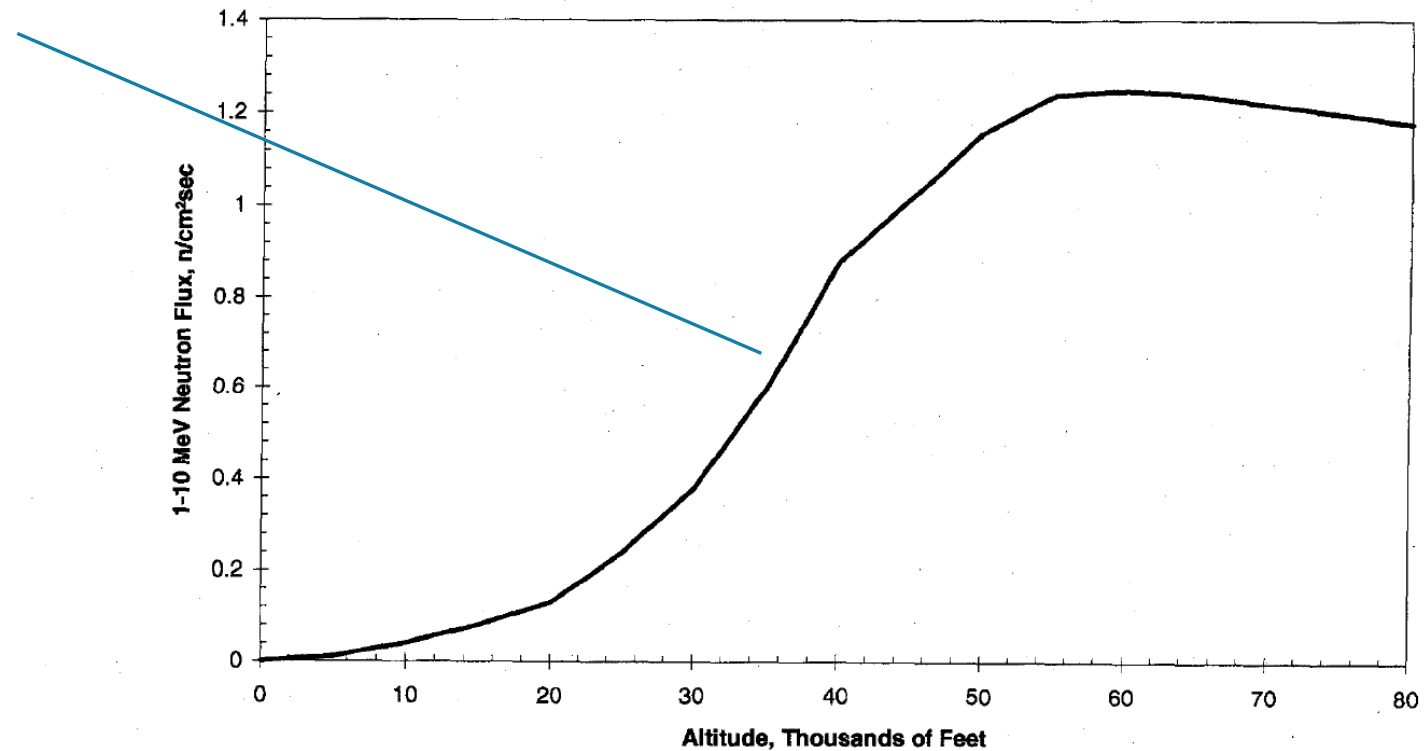


Fig. 2. The 1-10 MeV atmospheric neutron flux as a function of altitude based on aircraft and balloon measurements [2].

THE EFFECT OF LATITUDE ON NEUTRON FLUX

Not quite as bad as altitude, but still different at the poles than the equator

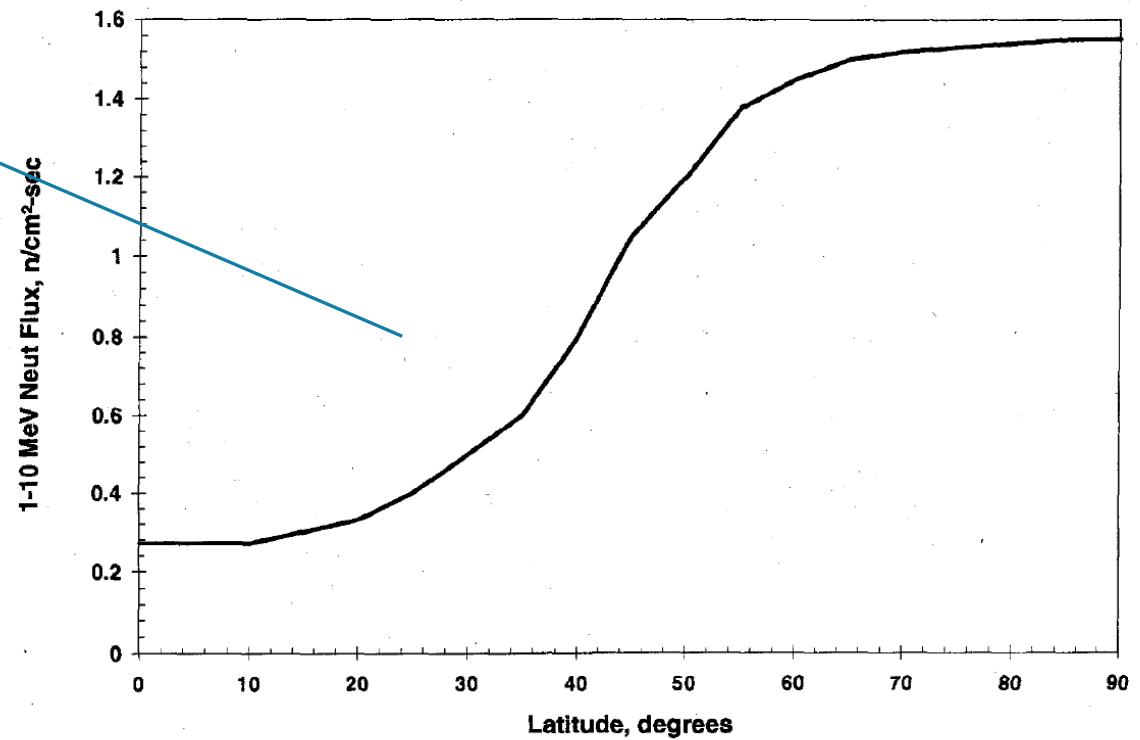


Fig. 3. The 1–10 MeV neutron flux as a function of geographical latitude based on aircraft neutron measurements and the vertical rigidity cutoffs of Smart and Shea [4], [5].

NEUTRON SPECTRUM IN NYC

Measured data points vs. the analytical fit

Relatively flat spectrum when viewed on a linear scale

Surroundings cause so many issues that most of the measured spectra are measured outside

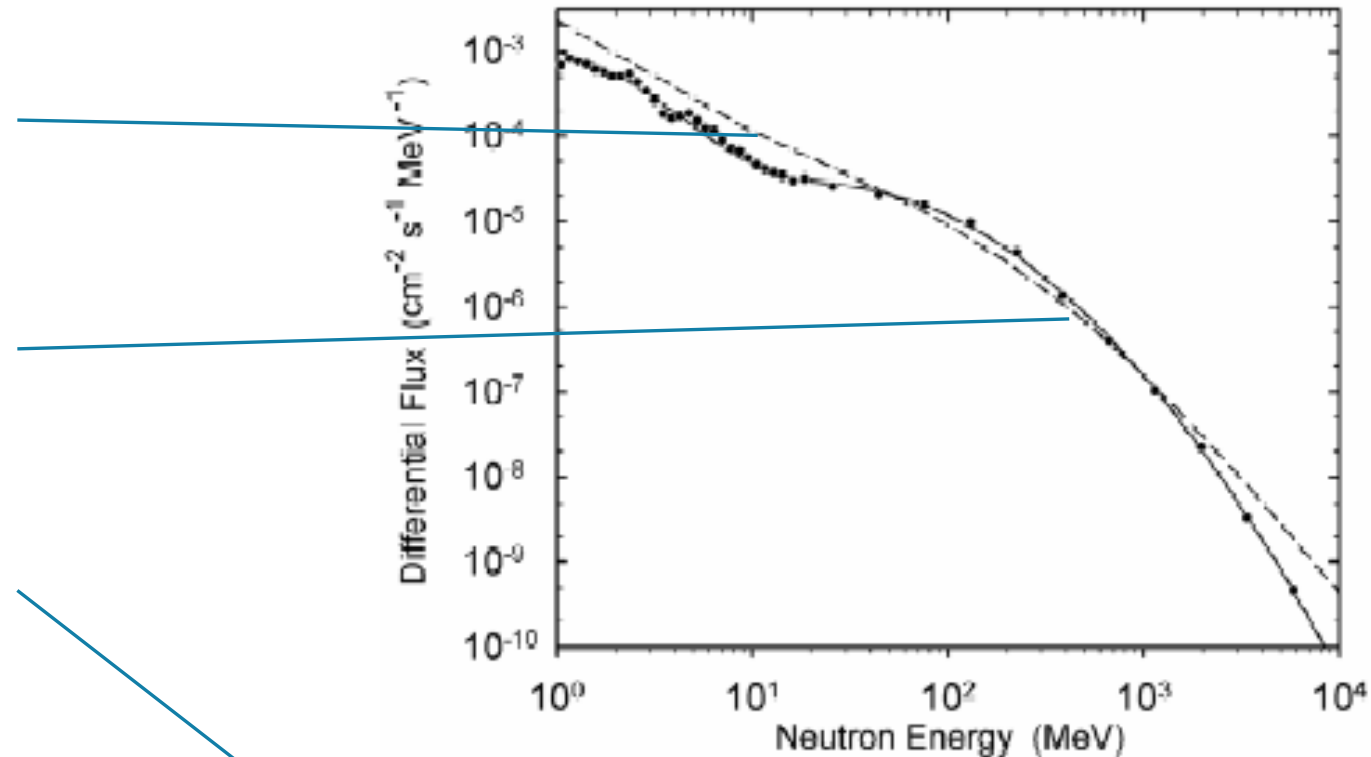


Figure A.2.1 — The differential flux of cosmic-ray-induced neutrons as a function of neutron energy under reference conditions (sea level, New York City, mid-level solar activity, outdoors). The data points are the reference spectrum, the solid curve is the analytic fit to the reference spectrum, and the dashed curve is the model from the previous version of this standard, JESD89 (2001).

FAST NEUTRON SPECTRUM IN NYC

JESD89 vs. JESD89A: the original version had issues with the 0.1-10 MeV neutrons

Histogram measurements, analytical fit

There is approximately the same amount of flux from 0.1 -10 MeV than 10-1000 MeV

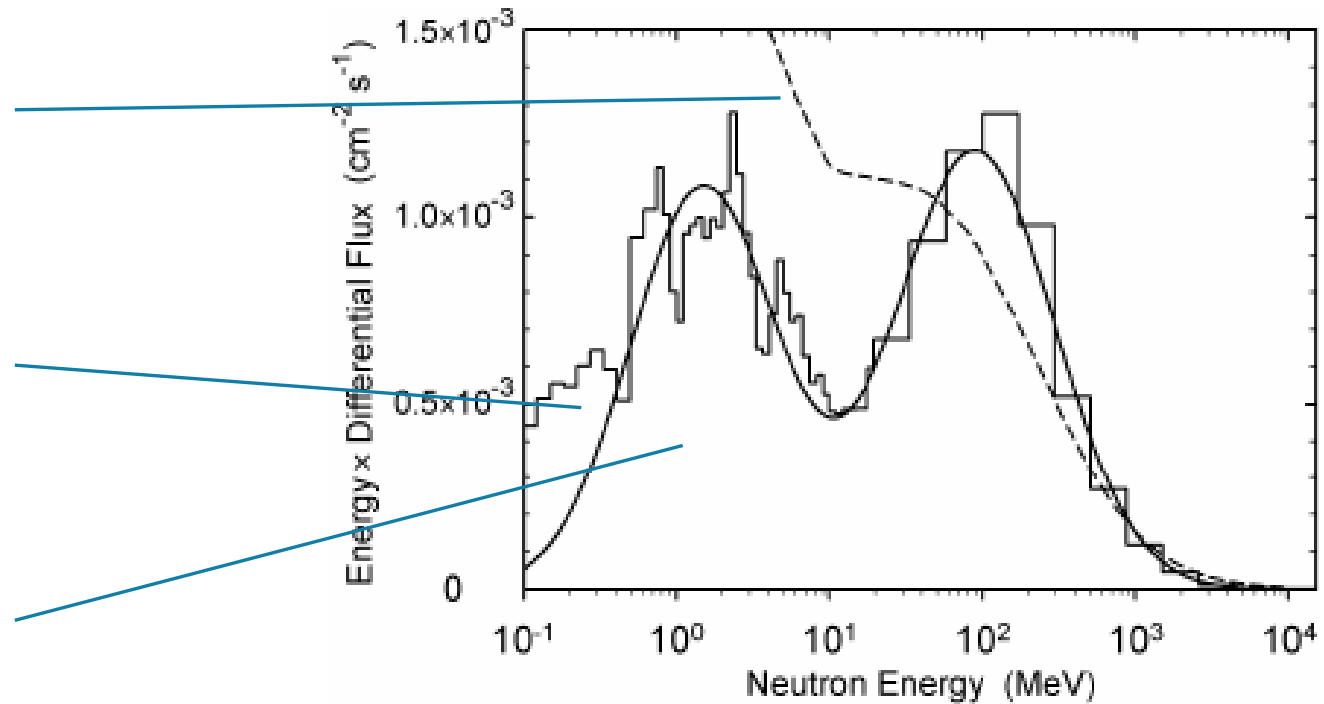


Figure A.2.2 — Reference spectrum of cosmic-ray-induced neutrons plotted as energy times differential flux as a function of neutron energy. The histogram is the reference spectrum, the solid curve is the analytic fit to the reference spectrum, and the dashed curve is the model from the previous version of this standard, JESD89 (2001).

SCALING FLUX FOR DIFFERENT LOCATIONS

The expression for F_B comes from theoretical calculations [20, 21] that were done only for the extreme conditions of solar modulation: quiet sun, when the terrestrial cosmic ray flux is at its peak, and active sun, when the terrestrial cosmic ray flux is at its minimum. For these two conditions,

$$F_{B,\text{quiet}}(R_c, h) = 1.098 \left[1 - \exp(-\alpha_1 / R_c^{k_1}) \right] \quad (\text{A.6})$$

and

$$F_{B,\text{active}}(R_c, h) = 1.098 \left[1 - \exp(-\alpha_2 / R_c^{k_2}) \right] \times \left[1 - \exp(-\alpha_1 / 50^{k_1}) \right] / \left[1 - \exp(-\alpha_2 / 50^{k_2}) \right], \quad (\text{A.7})$$

where the parameters α and k are given by

$$\alpha_1 = \exp[1.84 + 0.094h - 0.09 \exp(-11h)], \quad (\text{A.8})$$

$$k_1 = 1.4 - 0.56h + 0.24 \exp(-8.8h), \quad (\text{A.9})$$

$$\alpha_2 = \exp[1.93 + 0.15h - 0.18 \exp(-10h)], \quad (\text{A.10})$$

$$\text{and } k_2 = 1.32 - 0.49h + 0.18 \exp(-9.5h). \quad (\text{A.11})$$

Unlike Equations A.2 – A.5, Equations A.6 – A.11 use barometric pressure, h , in bar (1 bar = 10^5 Pa) instead of depth or pressure in millibar: $h = p/1000$.

Or use seutest.com

SEVERAL MEASUREMENTS OF DIFFERENT LOCATIONS

Fast neutron flux is pretty stable, when corrected for location.
NOTE: All on ground

Epithermals and thermals have some location variation, which is not understood

Thermal flux is roughly the same as 0.1-10 MeV and 10-10000 MeV flux. There can be a lot of thermals even outside. Building materials only make more, too.

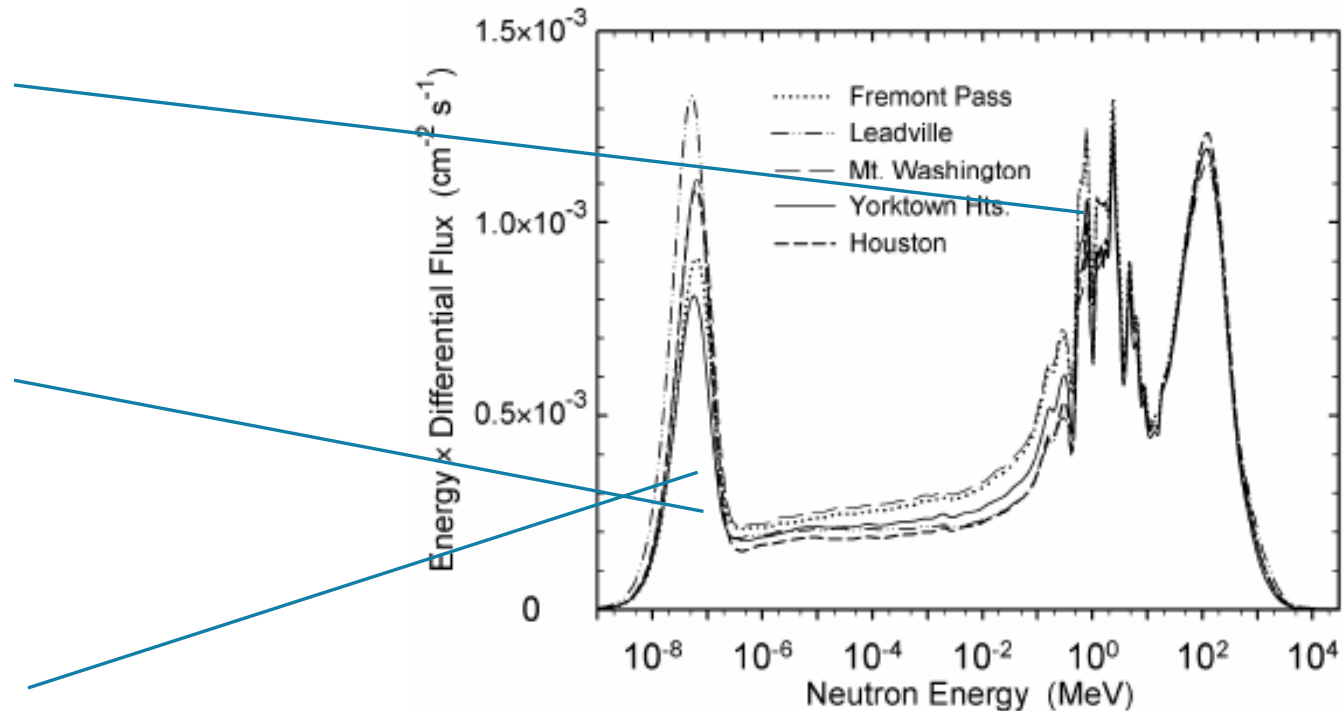
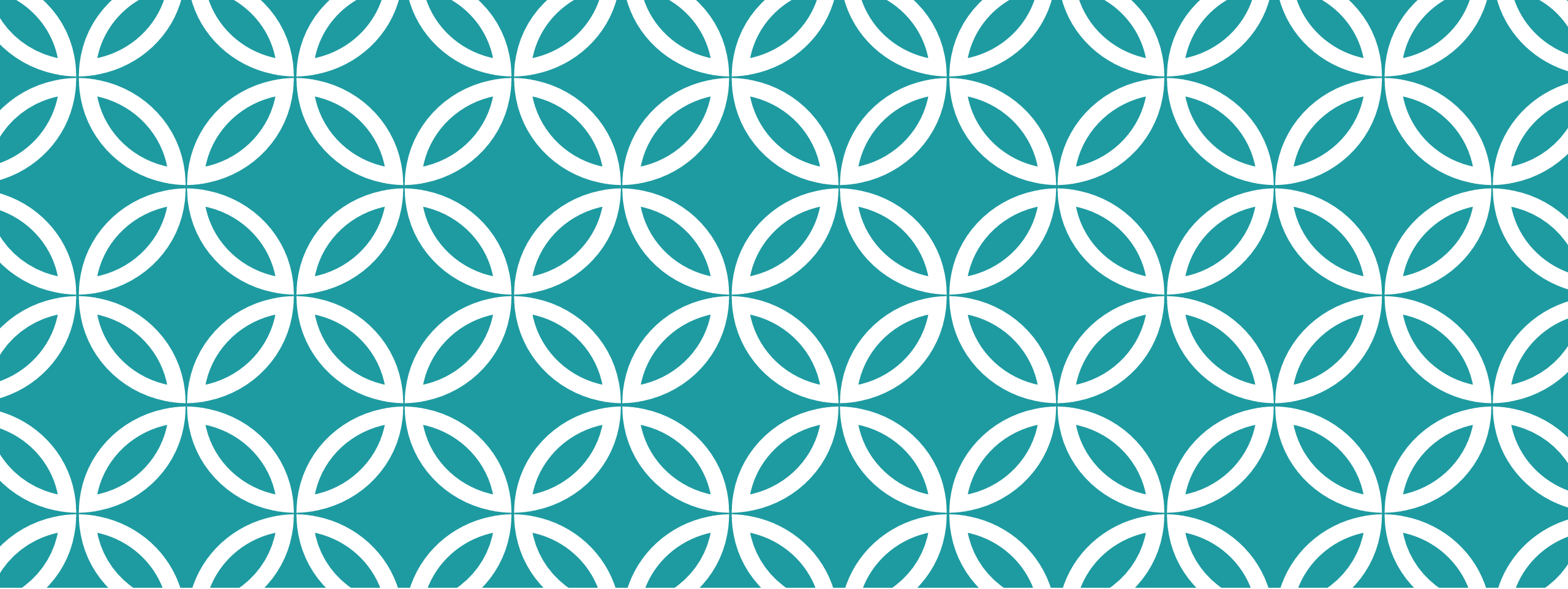


Figure A.4.1 — Spectra of cosmic-ray-induced neutrons measured at five locations. Each spectrum has been scaled to sea level and the cutoff of New York City and plotted as energy times differential flux as a function of neutron energy.



THE EFFECT OF BUILDING MATERIALS



THERMALS ARE VERY SENSITIVE TO LOCATION AND WATER

Thunderstorms matter but water doesn't?

4x variation in thermal flux in roughly the same location

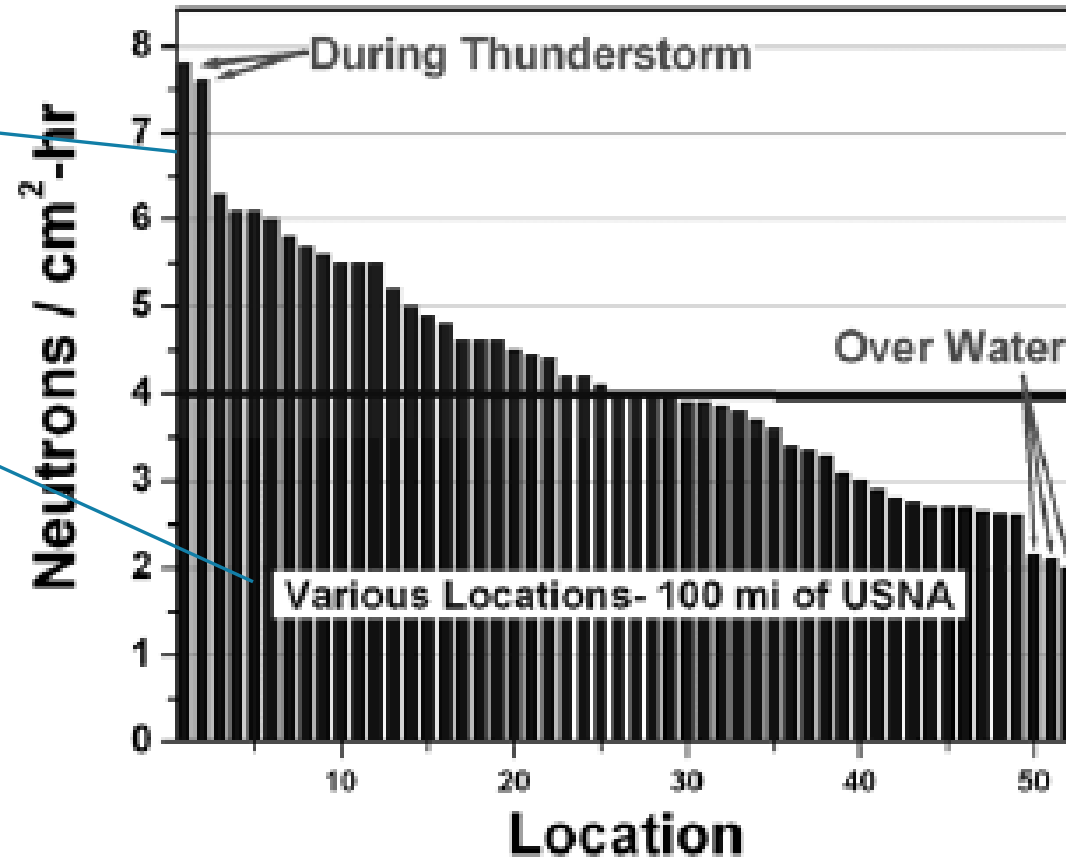


Figure A.4.2 — Thermal neutron flux measured at 52 sites near sea level within 160 km (100 miles) of the U.S Naval Academy in Annapolis, MD (39.0° N, 76.5° W) [18]. The fluxes shown have not been adjusted to the reference conditions.

THE EFFECT OF BUILDING MATERIALS

For Concrete, in a large building it was found that two 15-cm (6-inch) slabs (plus associated roofing, ceiling, and flooring material, ductwork, etc. in an industrial building) reduced the high-energy portion ($E > 10$ MeV) of the neutron spectrum by a factor of 2.3, while the total neutron flux was reduced by a factor of only 1.6. As they penetrate the concrete, low-energy neutrons are scattered, thermalized, and absorbed, but the high-energy neutrons are attenuated by interactions which cause the nuclei in the shielding to emit neutrons with energies in the MeV range, regenerating the low-energy portion of the neutron spectrum.

This is often called “replacement theory.” Shielding causes the spectrum to shift down in energy, but maintain the same basic shape

MORE ON CONCRETE

For the portion of the spectrum above 10 MeV, the attenuation by horizontal concrete layers above the point of interest may be estimated using exponential attenuation with an attenuation length of 1.2 feet or 0.37 m:

$$\Phi = \Phi_0 \exp(-x/0.37) \quad (\text{A.12})$$

where Φ and Φ_0 are the attenuated and initial flux and x is concrete thickness in meters. Assuming a density of 2.3 g cm^{-3} , the mass attenuation length of concrete floor slabs is roughly 85 g cm^{-2} . The lower energy portion of the neutron spectrum does not decrease as fast; the attenuation length for the total flux is about 0.65 m or 150 g cm^{-2} . The cosmic ray secondary protons are presumably attenuated more than the neutrons.

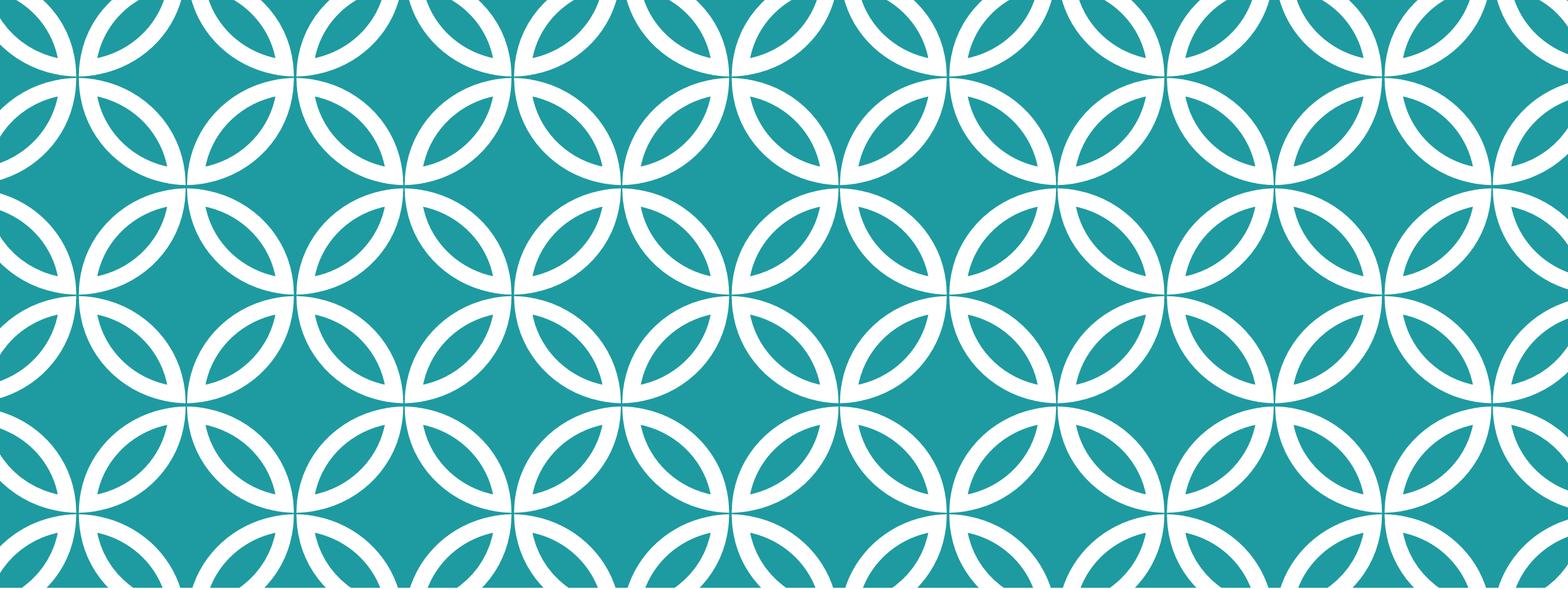
NEUTRONICS

More classical than protons

Difficult to shield without a lot of hydrogen

What we know about neutronics is mostly for outdoors

- Altitude and latitude are the big factors
- But so is longitude, geomagnetic rigidity, solar cycle, and thunderstorms
- Indoors gets confusing because of building materials



OPEN QUESTIONS



E_0

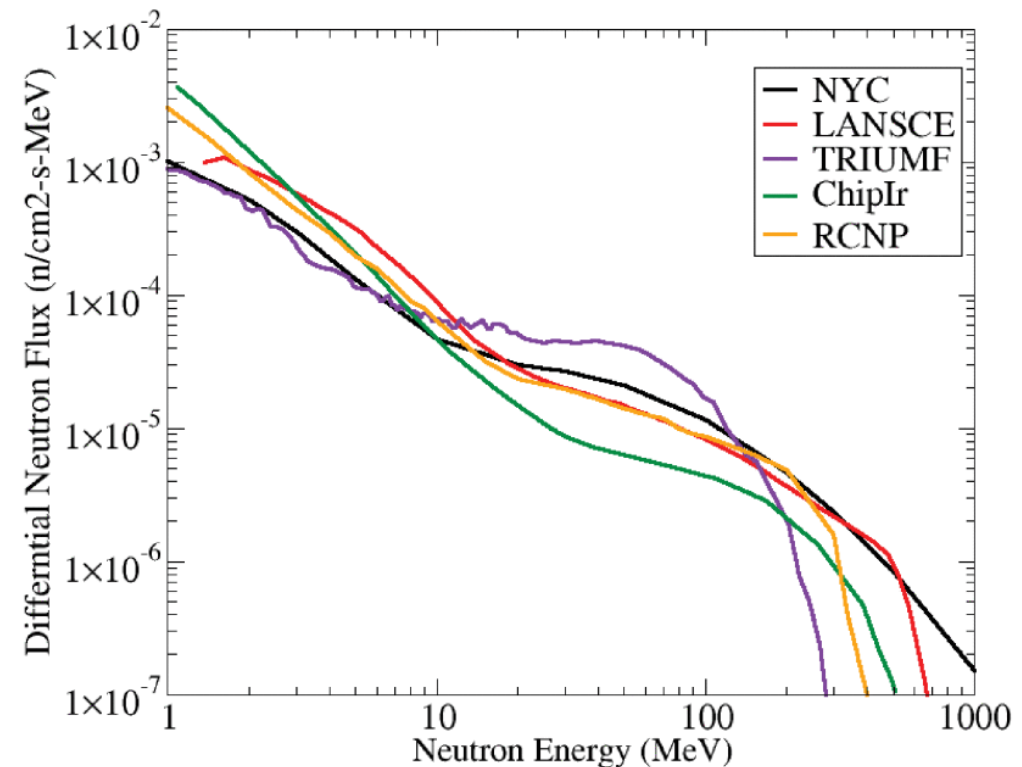
All of the have different E_0 and E_{\max}

LANL has been studying whether E_0 needed to be changed in the JESD89

- Many but not all electronics have onsets below 10 MeV, so the fluence is under counted
- All of the facilities have too many 1-10 MeV neutrons, so we might overcount fluence if we lower E_0
- We did not change it for JESD89B, because the information was contradictory

Open Questions:

- Can we make simplifications of the Weibull parameters based on feature size and/or effect?
- Can we fix the accelerator spectrum?
- Could something like a sensor response function help us out?
- Can we predict the error in broad spectrum testing without doing 1-10 MeV mono-energetic neutron testing
- Why does 1-10 MeV neutron sensitivities not look like 1-10 MeV proton sensitivities? What to do about the fit?



RECOIL BYPRODUCTS

There is very little information about the byproducts of proton and neutron Si interactions (Tang, and Hiemstra)

Open Questions:

- Did we really have enough information from the Tang paper to say that above 50 MeV the reactions are equivalent?
- What are the recoiling heavy ion species and energies based on proton and neutron incident energy?
- Is there some packaging aspect that we are not taking into account that makes 1-50 MeV protons and neutrons reactions different? What is the underlying physics?

DD + SEE

Open Questions:

- Does DD change SEE sensitivities: either increasing or decreasing?
 - The DD should increase the resistivity and might decrease SEL
 - Is that true of all effects?
 - There is some small amount of modeling that shows that SEB is worse under DD. Is that true in the wild?

FINS VS. PLANAR

Open Questions:

- Is there any difference in the onset for fin vs. planar?
- Is DD worse in smaller feature sizes?

B10

Open questions:

- How pervasive is it?
- Is there a way to determine how close the B10 needs to be from the sensitive volume?
- How different are the sensitive volumes for the B10 reaction vs. the Si reaction?
- Is there any way to predict this?